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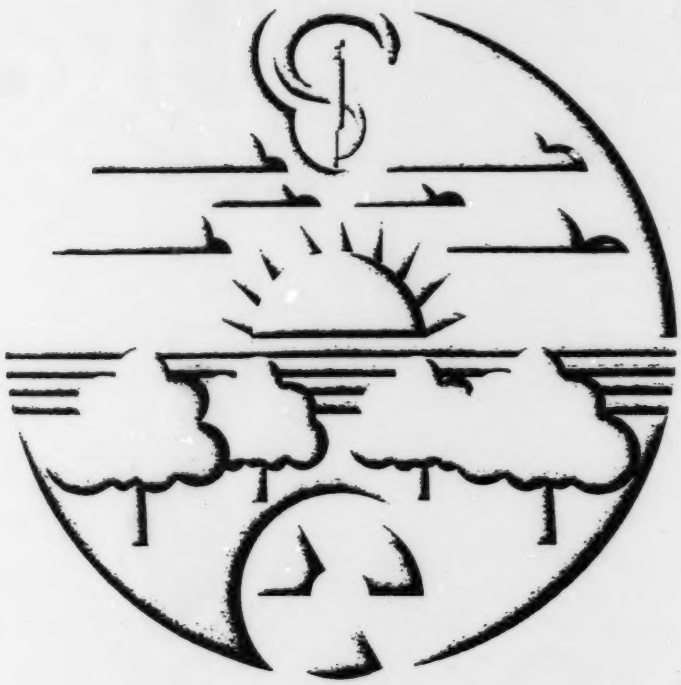
Guidelines for the Safe Use of Ultrasound
Part I
Medical and Paramedical Applications

88-EHD-59



Canada

SAFETY CODE - 23

GUIDELINES FOR THE SAFE USE OF ULTRASOUND
PART I
MEDICAL AND PARAMEDICAL APPLICATIONS

1987 UPDATE

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FOREWORD

The purpose of this Safety Code is to provide guidance to operators on the safe use of ultrasound. The document provides basic information on ultrasound characteristics, applications, biological effects, recommended safety procedures and protection measures for medical applications. These guidelines cannot cover all possible applications or exposure situations, nor can they substitute for the exercise of good judgement. It is recognized that the recommendations presented here may need to be modified in unusual circumstances.

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1. INTRODUCTION

Ultrasound is a form of mechanical energy (sound) having frequencies above the human hearing range, approximately 20 kilohertz (kHz). Acoustic radiation is usually categorized with non-ionizing radiations, since it does not cause the production of ion pairs in irradiated material.

Ultrasound has found widespread application in medicine. Figure 1.1 provides an overview of some medical applications of ultrasound in relation to the frequency ranges in which they are used.

In medical applications, the use of ultrasound involves human exposure either incidentally or as an essential part of the procedure. It is important to ascertain whether such exposure is potentially hazardous and minimize or control exposure accordingly. To that end, the purpose of this document is to provide a summary of uses of medical and paramedical ultrasound, to review briefly the observed effects of ultrasound on exposed biological systems, and to outline, as far as is possible with the present state of knowledge, safe use guidelines. In addition, quantitative guidelines for diagnostic devices with the claimed purpose of fetal examinations are given in Appendix 2.

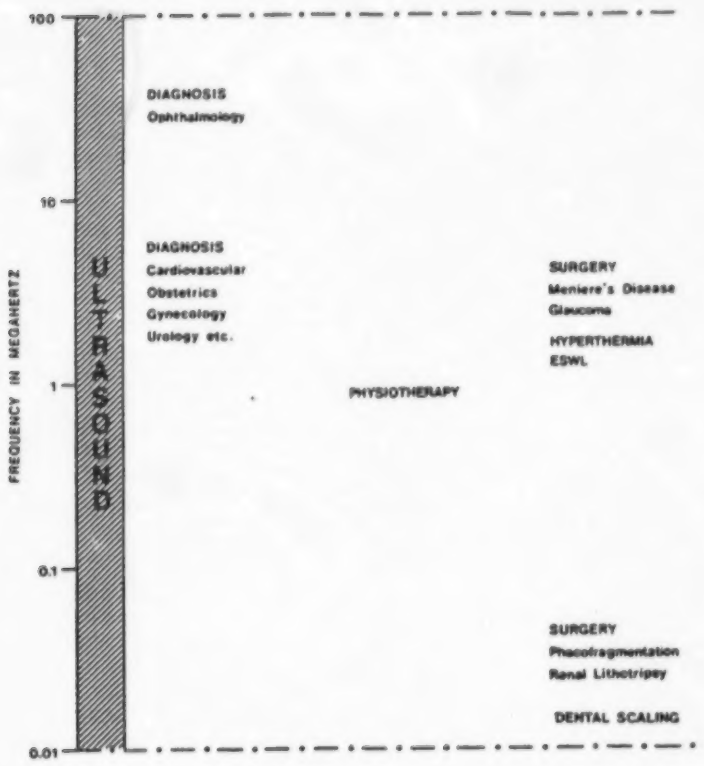
1.1 Basic Properties of Ultrasound

Ultrasound waves require a medium (solid, liquid or gas) in order to propagate. As they travel through the medium they cause disturbances consisting of alternate compressions and rarefactions (Figure 1.2). In a plane-travelling wave, the sum of distances corresponding to one compression and one rarefaction is one wavelength (λ). The frequency of ultrasound is described in terms of Hertz (Hz), where 1 Hz = 1 cycle per second. The relationship between ultrasound speed (c), wavelength (λ) and frequency (f), is expressed by the equation

$$c = f\lambda$$

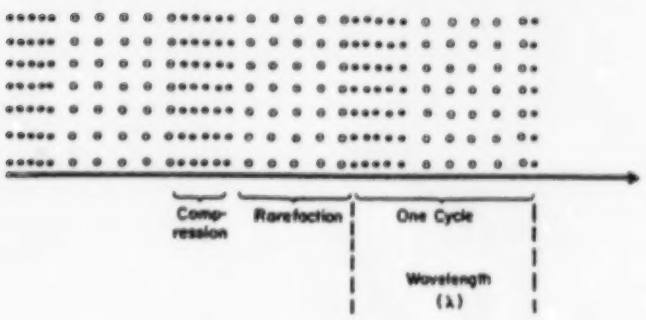
which shows that, as frequency increases, wavelength decreases.

Figure 1.1 Medical Applications of Ultrasound



The applications are shown in their ultrasonic frequency range

Figure 1.2 Diagram of Ultrasound Waves Illustrating Compressions and Rarefactions



A measure of the degree or strength of the disturbance is the amplitude (A), the maximum value of the acoustic pressure, (acoustic pressure is the value of the pressure minus the ambient pressure). Amplitude or Intensity (I) of ultrasound can be expressed in terms of decibels (dB). This is a relative number based on the formula:

$$dB = 20 \text{ Log } \frac{A_2}{A_1} \quad \text{or} \quad dB = 10 \text{ Log } \frac{I_2}{I_1}$$

where Log is the logarithm to base 10, A_1 and A_2 represent the amplitudes being compared, and I_1 and I_2 similarly represent the intensities. Intensity, which is the spatial concentration of power, is usually measured in watts per square centimeter (W/cm^2), or milliwatts per square centimeter (mW/cm^2).

While there are several different types of ultrasound waves, longitudinal waves are of primary interest in medical ultrasound. In longitudinal waves, the particle motion is parallel to the direction of propagation of the ultrasound

wave. Another type of ultrasound wave, which is of some importance to ultrasound heating, is the shear wave which occurs in bones and at bone-tissue interfaces. Shear waves have particle motion perpendicular (transverse) to the direction of the wave propagation.

1.2 Transmission Through Media

The velocity, impedance, attenuation and absorption of tissues, air and water are important quantities in the use of medical ultrasound since they determine patient exposure. These properties are described below. Table 1.1 contains values of velocity, impedance, attenuation and absorption in the megahertz (MHz) frequency range for selected tissues. More detailed compilations are given in NCRP Report No. 74[1].

Ultrasound beams can be refracted and distorted because of changes in the speed of sound between adjacent tissues. Ultrasound obeys Snell's law

$$\frac{\sin\phi_1}{\sin\phi_2} = \frac{c_1}{c_2}$$

where ϕ_1 and ϕ_2 are the angles of incidence and refraction respectively and c_1 and c_2 are the ultrasound speeds in the adjacent media. The speed (c) of ultrasound depends on the bulk modulus (K) and density (ρ) via

$$c = (K/\rho)^{1/2}$$

The speed of sound in bone is more than double that in soft tissue. This is due to the much larger bulk modulus (lower compressibility) of bone, which more than compensates for its higher density.

The reflection of ultrasound at an interface between two tissues or media is determined by the impedance mismatch. For ultrasound propagating perpendicular to the interface

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2}$$

Table 1.1 Table of Acoustic Properties of Tissue, Air and Water at 37°C and 1 MHz

Tissue	Speed ms^{-1}	Impedance [a] $(kgm^{-2}s^{-1})x10^6$	Attenuation [b] $(dBcm^{-1})$	Reference
Air	330	0.0004	1.6	Pierce, 1981[3]
Water	1524	1.5	0.002	Greenspan & Tschiegg, 1959[4] Pinkerton, 1947[5]
Blood	1570	1.66	0.15	Goss et al. 1980[6] Narayana et al. 1984[7]
Muscle	1580	1.64	1.5[c] 3[d]	Wells, 1977[8] Nassiri et al. 1979[9]
Fat	1460	1.34	1	Wells, 1977[8] Chivers and Hill, 1975[10]
Bone	3500	7.7	10 10	Goss et al. 1980[6] Wells, 1977[8]
Tendon			4.8[e]	Goss et al. 1979[11]

a Densities from ICRP Publication 23[2].

b Attenuation for air and water varies with the square of the frequency while tissue is usually assumed to have an approximately linear dependence on frequency (f).

c Ultrasound beam propagation is perpendicular to muscle fibres.

d Ultrasound beam propagation is parallel to muscle fibres.

e Absorption is 1.2 dB/cm from Goss et al. 1979[11].

where R is the pressure amplitude reflection coefficient (the ratio of pressure amplitude in the reflected wave to the incident wave) and Z_2 and Z_1 are the impedances of the adjacent media. The impedance (Z) of a material is given by

$$Z = \rho c$$

The large reflections at an air/solid or air/liquid interface make it necessary to avoid any air space between the ultrasound applicator and the patient. Therefore a liquid medium is required to couple the applicator and the patient.

The properties of absorption and attenuation are also important to ultrasound in medicine since they determine the intensity of the ultrasound at a given position in the body and the amount of energy deposited at that position. Attenuation is due to both absorption and scattering of the ultrasound by the medium. Absorption of ultrasound converts ultrasonic energy into heat in the medium. Scattering of ultrasound occurs at interfaces with different impedances. These interfaces are small with respect to ultrasonic wavelength. Generally attenuation increases with increasing ultrasonic frequency.

The large reflection at an air/solid or air/liquid interface and the relatively large attenuation of air at MHz frequencies minimize the likelihood of significant ultrasound exposure to the operator in the absence of a coupling medium.

1.3 Generation of Ultrasound

Ultrasound is generated by transducers which transform electrical energy into ultrasonic energy. Transducers for imaging and physiotherapy are most commonly made of piezoelectric ceramics (ferroelectrics) such as lead zirconate titanate. The piezoelectric effect converts a voltage to a mechanical strain. The application of an oscillatory voltage across the ceramic causes it to vibrate in all directions but particularly in directions perpendicular to the crystal surface. The vibrations of the ceramic cause compressions and rarefactions in the adjacent fluid leading to the generation of ultrasound. To control the properties of the

beam which propagates in the forward direction (i.e. into the patient) a backing is applied to the transducer. In the continuous wave mode, high efficiency is often obtained by using a totally reflective air backing. In this way, all the ultrasonic energy is available to propagate into the load (i.e., the patient). For the very short pulses required in ultrasound imaging, a heavy damping backing, such as a tungsten epoxy mixture, is used. In diagnostic imaging, efficiency of ultrasound transmission (and reception) is improved by the addition of layers of material which match the acoustic impedance of the transducer to that of water.

The basic designs of ultrasound transducers are shown in Figure 1.3[12]. In physiotherapy the transducer is usually a circular disk (Figure 1.3 (a)). For diagnostic ultrasound a wide variety of transducers are used. The most common of these are 1.3 (b) the dual element, (c) the bowl or spherically focused transducer and (d) linear arrays of narrow rectangular transducers. Design (b) is used for continuous wave (cw) Doppler devices (Section 3.2) since, in cw mode, one transducer is needed for transmission and one for reception. Designs (c) and (d) are used for imaging and pulsed Doppler. The spherically focused transducer may be in the form of an annular array which provides electronic focusing over a large depth of field. Linear arrays may also be electronically focused and scanned. When electronic or geometrical focusing is not possible, focusing of transducers may also be done with the use of acoustic lenses.

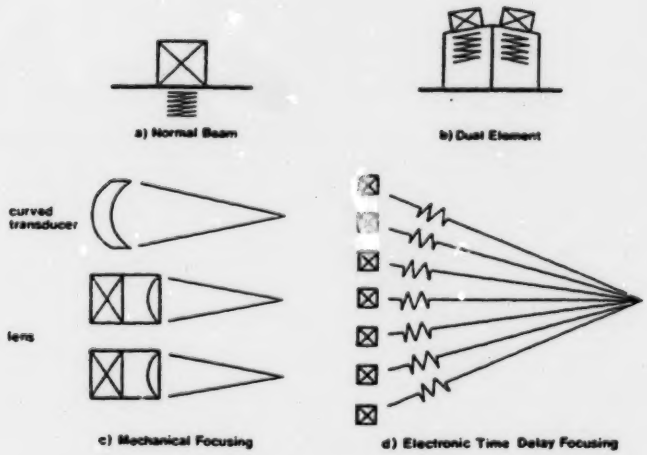
More detailed discussions of transducer design and performance can be found in several reviews[8,13,14].

1.4 Measurement of Ultrasound

A number of methods exist for the measurement of properties of ultrasonic fields. Two methods which are commercially available and of most use at present are the radiation force balance and the hydrophone.

The radiation force balance is used to measure the total power radiated from an ultrasound emitting device at MHz frequencies.

Figure 1.3 Schematic Illustration of a Variety of Transducer Configurations Used for Diagnostic Ultrasound



From reference 12

In one common design the ultrasound beam impinges normal to a perfectly absorbing target while in another common design it is incident at 45° to a perfectly reflecting target. In both cases the radiation force (F) and the total power (W) are related by

$$F = W/c$$

where c is the speed of ultrasound in the propagation medium. The balance measures the ultrasound force either electromechanically or purely mechanically.

The hydrophone is a small piezoelectric element which provides a spatially localized measurement of acoustic pressure as a function of time. The hydrophone acts as a detector via the piezoelectric effect; a mechanical stress generated in the ultrasonic field is converted to a voltage. The voltage produced by the hydrophone is proportional to the acoustic pressure at the active element. The piezoelectric element is usually the ceramic lead zirconate titanate or the polymer film polyvinylidene difluoride (abbreviated PVDF or sometimes PVF2). Ceramic hydrophones have the advantage that they are relatively inexpensive, very sensitive and durable. Their major disadvantage is that they do not have a flat frequency response. For this reason, their use is discouraged except for continuous wave measurements.

The PVDF hydrophones are more expensive and less sensitive than those made of ceramic but in other regards they have much superior measurement characteristics. In particular, they have a nearly flat frequency response over a large bandwidth. (The flatness at frequencies greater than 15 MHz depends greatly on the design of the hydrophone.) The short pulses used in ultrasound imaging contain a broad band of frequencies and PVDF hydrophones are required to measure these pulses with reasonable accuracy.

More detailed discussion of the radiation force balance and hydrophone measurement techniques and calibration can be found elsewhere[15-17].

1.5 Ultrasonic Beam Properties

It is important to have an understanding of the spatial and temporal properties of the ultrasound beam. For physiotherapy, hyperthermia and some surgical applications, the heating pattern created by the ultrasound beam is of major importance. In diagnostic ultrasound, image quality depends mainly on the axial and lateral resolution throughout the image. Lateral resolution is determined by the spatial

characteristics of the beam while axial resolution depends on the pulse width. Properties of ultrasound beams for different transducer geometries can be found in several reviews[13,14]. Some properties of the ultrasound field from the best understood geometry[18], the circular disk, are shown in Figure 1.4. This geometry is of practical importance since it is widely used in physiotherapy devices. Figure 1.4 shows the complex behaviour of the beam in the near field and the existence of a single axial intensity peak occurring at some distance from the transducer. Beam divergence is decreased with both higher frequencies and larger diameter crystals.

Figure 1.4 Ultrasound Beam from an Ideal Stiff Planar Disk Transducer

Near and far fields are illustrated. Ring diagrams represent the cross-sectional intensity distribution at selected depths. The last plot is of the normalized axial intensity distribution. The transducer diameter is 10 wavelengths.

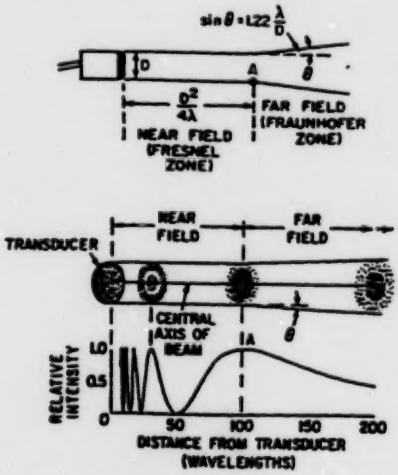
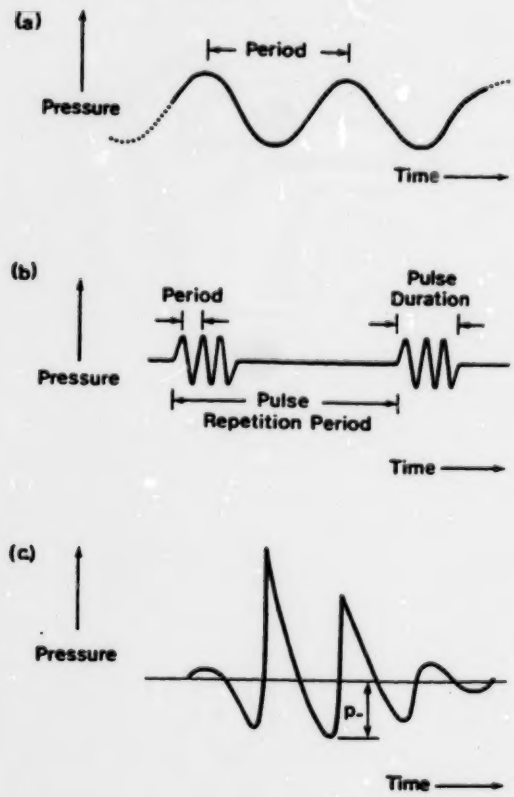


Figure 1.5 Illustration of Temporal Properties of Ultrasound Waveform



(a) Continuous wave (cw) ultrasound on expanded scale.
(b) Pulsed ultrasound. Both (a) and (b) are from AIUM Publication 316[19].
(c) Typical pulse measured at focus of diagnostic imaging transducer. From IEC Draft Standard[20].

In physiotherapy applications with cw or long pulses of ultrasound, standing wave fields (a superposition of stationary and travelling waves) can also be formed. These could occur due to highly reflective bone/tissue or tissue/air interfaces close to the transducer. Stationary waves are characterized by a spatial pattern of pressure nodes and antinodes and by zero net time averaged flux of energy across any surface within the standing field. The maximum acoustic pressures and radiation forces can be greatly increased in standing waves as compared to travelling waves.

1.6 Exposure Parameters

Exposure parameters, properties of the ultrasound beam measured under travelling wave conditions in water, serve as a starting point in defining the extent to which a biological system has been exposed to ultrasonic energy, i.e., they are the basis for determining an ultrasonic dose. The exposure parameters should have the following properties: (i) be measurable, (ii) be representative of the behaviour of the output from a transducer and (iii) bear some relevance to biological effects. The main exposure parameters are briefly reviewed here. Other excellent reviews have appeared previously[1,19]. Precise definitions can be found in existing standards[16,20].

The ultrasonic power is probably the simplest parameter conceptually. It is the total amount of ultrasonic energy radiated per unit time by the transducer. Averaging this power over all time yields the time average ultrasonic power.

In general, the ultrasound beam is not spatially uniform and therefore the patient will not be irradiated uniformly with ultrasound. Hence, the intensity, which is the spatial concentration of the power, is an important quantity. Intensity is the amount of energy per unit time and per unit area passing through a point in the medium being irradiated. Ideally, the intensity should be specified at every point in the field and at every instant of time (instantaneous intensity) during the irradiation, but this is not practical, either for the purpose of measurement or for the purpose of supplying output

information to the user. Useful exposure parameters have arisen from appropriate averages of the instantaneous intensities. The averages and /or maxima are taken spatially and/or temporally. The time averaged intensities give an indication of the thermal effects to be expected while the pulse related intensities or acoustic pressure quantities tend to be indicative of the cavitation effects. Exposure parameters are defined for both continuous wave (cw) and pulsed operation. Idealized acoustic waves and pulses are shown in Figures 1.5(a) and (b) and a typical pulse from a diagnostic imaging transducer is shown in Figure 1.5(c). These Figures illustrate the important temporal characteristics of these waveforms.

For both practical and historical reasons the exposure parameters for diagnostic and therapeutic ultrasound are somewhat different. For physiotherapy, the ultrasonic power, W, is defined as $W=E_T/T$ where E_T is the total energy emitted within a period and T is the period of the carrier wave (see Figure 1.5). For cw systems, this power is equivalent to the power measured with a radiation force balance. For pulsed operation the maximum value of ultrasonic power in time (temporal maximum) is the appropriate exposure parameter. This is to account for possible cavitation effects which could occur due to high intensities during the pulse. The temporal maximum ultrasonic power cannot be directly measured from a radiation force balance measurement, but must be derived from measured waveforms as in Figure 1.5(b). The effective intensity (temporal maximum or temporal average) is defined as W/(ERA) where ERA is the effective radiating area of the applicator and W is the ultrasonic power (temporal maximum or temporal average). The ERA and other exposure parameters for physical therapy devices are carefully defined in Appendix 1.

For diagnostic ultrasound a number of exposure parameters have been suggested. Although the most appropriate parameters have yet to be established, there are three which have been most commonly used: (i) P, time-averaged ultrasonic power, (ii) I(SPTA), spatial peak temporal average intensity, and (iii) I(SPPA), spatial peak pulse average intensity. Time-averaged power has been defined above. The

intensities are derived from acoustic pressures measured with a hydrophone. It is assumed that the instantaneous intensity, I(t), is proportional to $p^2(t)$, the square of the instantaneous acoustic pressure. The quantity I(SPTA) is the largest time-averaged intensity which can be measured anywhere in the ultrasonic beam. The time averaging is done over a period for cw and over a pulse repetition period for pulsed ultrasound (see Figure 1.5). The quantity I(SPPA) is typically three orders of magnitude greater than I(SPTA). For I(SPPA), the intensity is averaged over the pulse duration (see Figure 1.5(b)). Another parameter gaining wide acceptance is p_- (or p_r), the negative peak pressure amplitude[20]. This parameter may be particularly useful because it is likely to be a reasonable indicator of transient cavitation and it is very insensitive to the details of the high frequency response of the PVDF hydrophone[21]. These and other exposure parameters are defined in the AIUM/NEMA Safety Standard[16], the NCRP Report No. 74[1] and the IEC draft standard on ultrasound field characteristics[20].

In addition to intensity and acoustic pressure, dwell time is also an important exposure parameter. It is defined as the amount of time during an examination that the ultrasound beam remains in one place (for a static transducer), or the amount of time the ultrasound scan plane remains in one place (for real-time systems).

2. BIOLOGICAL EFFECTS OF ULTRASOUND

In order to assess the potential for medical ultrasound to cause adverse health effects, it is necessary to summarize the status of our knowledge on the biological effects of ultrasound. Only a brief summary can be given here. However, there is a considerable number of relatively recent reviews[1,19,22-32] for the reader interested in more details.

A vast array of ultrasonically induced biological effects has been observed; some of these are given in Table 2.1. However, it is difficult to establish the relationship between these observed biological effects and adverse health effects on human beings. First, many observations have not been reproducible in other laboratories. For example,

cavitation, the interaction of ultrasound with bubbles, has been a primary mechanism in many in vitro biological effects. The extent of cavitation depends on the presence of stabilized gas bubbles or other nuclei from which gas bubbles may grow and these have not generally been controlled by the experimenter. Another difficulty is that, until recently, measures of ultrasound exposure (exposimetry) used in these experiments have often been inadequate. Furthermore, the acoustical properties of the biological system under study influences the extent to which ultrasound can affect the system. For example, cavitation studies on insects cannot be extrapolated to humans.

Despite these difficulties, there has been some progress in estimating the potential of ultrasound to cause adverse health effects. The approaches have been in the following areas; (i) human studies (ii) mechanisms of biological effects and (iii) extrapolations from mammalian studies.

2.1 Human Studies

Table 2.2 summarizes the results of some human epidemiological studies. These results, and other results from human biological effects studies using diagnostic ultrasound[1,29], have not yielded any confirmed adverse health effects due to ultrasound.

Three recent human studies raised new questions about potential health effects of diagnostic ultrasound: one study alleged premature ovulation after follicular monitoring with diagnostic ultrasound[39], and two other studies suggested decreased fertility in artificial insemination procedures after exposure to diagnostic ultrasound[40,41]. However, the flaws in these studies cast considerable doubt on any causal relationship between ultrasound exposure and the alleged effects.

It should also be recognized that the studies of Table 2.2 suffer from a number of limitations. For example, in the surveys of the users of diagnostic ultrasound by Ziskin and Benwell[36,37], it is not known how diligently the users were looking for adverse effects nor is it known what

Table 2.1 Reported Biological Effects Induced by Exposure to Ultrasound in Experimental Studies

Biological Level of Organization	Description of Effect
Biological Macromolecules	Molecular degradation
	Enzyme inactivation
	Enhancement of enzyme activity
Cells	Cell disruption
	Thrombocyte disruption (clot initiation)
	Dislodgement of ribosomes
	Release of enzymes from lysosomes
	Rupture of nucleolus
	Disruption of mitochondrial cristae
	Chromosomal anomalies
	Mitotic delay
	Increase of cell membrane permeability
	Intracellular streaming
	Abnormal cell division
	Cell surface changes
Tissues and Organs	Selective heating of peripheral nerves
	Reduction of nerve action potential
	Tissue edema
	Hemorrhage
	Decreased glycogen in muscle and liver
	Formation of cataracts
	Blood flow stasis
	Induction of congenital anomalies
	Retardation of fetal growth
	Increased rate of tissue regeneration
	Lesions
Animals	Fetal weight loss
	Hind limb and tail paralysis
	Increased heart rate
	Retardation of growth
	Delayed neuromuscular development
	Death

The effects are grouped according to biological organization.

Table 2.2 Table of Selected Epidemiological Studies

Type of Study	Effect	Result	Reference
Prospective Exposed/ Matched Control	Dyslexia, Reduced Birth Weight	No significant effect	Stark et al. 1984[33], NIH[30]
Retrospective Case/Control	Childhood Leukemia	No significant effect	Kinnier-Wilson and Waterhouse, 1984[34]
Retrospective Case/Control	Childhood Leukemia	No significant effect	Cartwright et al. 1984[35]
Survey	Adverse health effects	None detected	Ziskin, 1972[36]
Survey	Adverse health effects	None detected	Benwell, 1981[37]
Randomized Controlled Trial	Short-term adverse health effects	None detected	Bakketeig et al. 1984[38]

endpoints were sought. Furthermore, only the study by Stark et al.[33] provides quantitative values for the exposure parameters of the diagnostic ultrasound devices. Some of the current exposure levels used in fetal applications may be more than an order of magnitude greater than those used by Stark et al. (see Section 3.2).

A useful analysis of statistics in epidemiological studies is given in the NCRP Report No. 74[1]. This analysis makes the important point that surveys will only be sensitive to large increases in naturally occurring conditions or to conditions which are not naturally found in the general population. For an adverse condition which occurs naturally, a very large epidemiological study is required to find a small percentage increase in the effect even when the effect is easily observed. Furthermore any delayed effects (longer than 13 years after birth) would have escaped detection in the studies completed to date.

The situation for diagnostic ultrasound can be summarized as follows. So far, human studies have not established any health hazard due to diagnostic ultrasound exposure. However, limitations of the epidemiological studies and recent increases in exposure levels indicate the need for continued vigilance to detect subtle or long-term health effects due to diagnostic ultrasound exposure.

Unlike the situation with diagnostic ultrasound, there are no large scale epidemiological studies on the possible adverse effects of ultrasound used in physical therapy. Reports of ill effects are largely anecdotal. However in a survey by Health and Welfare Canada, over a period of one year, 80 out of an estimated 850 000 patients had reported adverse effects following ultrasound therapy[42]. The most common effects were pain and discomfort. Burns, heat, dizziness, nausea and fatigue were also reported in this survey. To summarize the results of human studies, short-term adverse effects due to ultrasonic physical therapy are known, although they occur only rarely. From these effects it is clear that caution in the use of ultrasound for physical therapy is advisable.

2.2 Mechanisms

Due to the difficulties encountered with epidemiological studies it appears useful to study the mechanisms of interaction of ultrasound with cells and tissue. It may be possible to identify suitable biological effects for observation in an animal model and to derive suitable endpoints for observation in an epidemiological study. Furthermore, if the mechanism of an effect is well understood and the appropriate acoustic properties are known, then it may be possible to estimate the risk to humans by extrapolation from animal studies.

Four mechanisms by which ultrasound causes biological effects in tissue will be considered here. They have been relatively well studied and have the potential to cause adverse health effects. The mechanisms are (i) thermal, (ii) stable cavitation, (iii) transient cavitation and (iv) radiation force.

The thermal mechanism is simply the heating of tissue due to the absorption of ultrasound. The extent of heating depends on the ultrasound intensity at the site of interest, the absorption coefficient of the tissue, and the heat loss via both conduction and blood flow.

Stable cavitation can be thought of as the gentle oscillation of a gas or vapour bubble i.e., the bubble alternately increases and decreases in size as it is acted upon by the ultrasound wave. There are very strong forces in the liquid medium near the gas bubble which can cause damage to cells.

Transient cavitation is the violent collapse of a rapidly growing gas bubble. Associated with the collapse are small regions of very high pressure and temperature which can form highly reactive chemical species such as free radicals. Either the violent collapse or the free radicals can damage cells.

Radiation force is an unbalanced net force due to the ultrasound. In a standing wave field this force can become large enough to cause blood cells to form bands in small blood vessels and to impede blood cell flow.

Table 2.3 Table of In Vivo Biological Effects - Selected Results Representative of Mechanisms

Mechanism	f MHz	I(SPTA) (W/cm^2)	t (min)	Animal Model	Effect	Reference
Thermal	0.9	5 cw	10	Dog Femur	Marrow Damage	Payton et al. 1975[43]
Thermal	1	1 cw	5	Pregnant Mouse	Fetal weight reduction	O'Brien, 1976, 1983[44,45]
Thermal	2	1 cw	5	Pregnant Mouse	Fetal weight reduction	Stolzenberg et al. 1980[46]
Radiation Force	3	1 cw	$8x10^{-4}$	Chick embryo	Blood Flow Stasis	Dyson et al. 1974[47]
Stable Cavitation	0.75	0.3 cw	2	Guinea Pig Hind-Limb	Bubbles observed in hind limb during exposure	ter Haar et al. 1982[48]
Transient Cavitation	2.25	0.04 p	2.5	Drosophila Larvae	Death of Larvae	Berg et al. 1983[49]

These results were selected to represent mechanisms of interaction between ultrasound and living systems. The cw refers to continuous wave ultrasonic exposures while p refers to pulsed ultrasonic exposures.

Table 2.3 shows some biological effects which are believed to be representative of these mechanisms.

It now appears likely that most biological effects observed in vitro in cell suspensions occurred as a result of the cavitation phenomenon[1]. The ultrasound intensity which will cause cavitation depends critically on the presence of small gas bubbles (so-called nucleation sites) and on other parameters such as the viscosity of the medium. The presence of stabilized gas bubbles can cause stable cavitation and cell lysis in vitro at remarkably low I(SPTA) values, on the order of a few mW/cm^2, for cw and pulsed (ms) ultrasound[50,51]. In a series of studies[52] and references therein) the delayed death of fruit fly larvae was demonstrated at I(SPPA) values on the order of 10 W/cm^2 for very low (on the order of 10 mW/cm^2) I(SPTA) intensities. These larvae naturally contain small gas-filled spaces in their trachea. The mechanism was believed to be transient cavitation. In addition, violent cavitation has been observed in distilled water for microsecond pulses of ultrasound[53,54].

Based on decompression experiments[55], there is some evidence that nucleation sites do occur in mammals. However, it is not clear whether such sites will lead to cavitation in mammalian systems. Gross et al.[56] failed to observe either stable bubbles or cavitation in the cardiovascular system of dogs whereas ter Haar and co-workers[48] observed evidence for cavitation in the hind leg of guinea pigs. An important area of research at present is the determination of the number of nucleation sites in mammals in vivo, whether they can give rise to cavitation (transient or stable), and whether such cavitation could cause adverse health effects.

Under the conditions used in physical therapy, with a stationary transducer and a very reflective interface near the transducer, it appears plausible that radiation force and cavitation mechanisms would be operative in humans.

Several significant adverse health effects could, in principle, be induced by these mechanisms using ultrasound. Based on experiments with small mammals, a temperature

increase to 41-42°C in the fetus could cause birth defects (teratological effects), particularly in the first six to eight weeks of gestation when the fetal organs are being formed[57]. Further evidence for adverse effects stems from the observations of reduced fetal weight in mice at I(SPTA) values of about 1 W/cm^2[44-46]. In humans, these heating effects are very likely to be negligible when using ultrasound imaging devices[1]. At present, there is uncertainty as to whether significant heating could occur with pulsed and cw Doppler devices used for fetal vascular studies.

The thermal mechanism can also cause bone damage in dogs using effective intensities toward the high end of those obtained with physical therapy devices (2.5 W/cm^2)[43]. Clearly, damage to bone and tissue could occur in humans if caution is not observed at these intensities. In addition, focal lesions have been observed in various mammalian tissues in vivo when long dwell times were used and I(SPTA) values in situ exceeded 10 W/cm^2 (see Figure 2.1). These latter effects form the basis for the use of ultrasound as a surgical tool. Such intensity and dwell time combinations should be above that used in physical therapy and are well above those used in diagnostic ultrasound.

At intensities used in physical therapy, two mechanisms, stable cavitation and radiation force, could contribute to the formation of a thrombus. Radiation force can cause blood cell flow stasis[47]. The forces during stable cavitation can cause platelet aggregation in vitro[50]. However, it is unlikely that this latter mechanism occurs in vivo in blood[56].

Genetic damage is a major concern when considering the possibilities of delayed adverse health effects due to a physical agent. A number of assays are available to test for DNA damage. Some of these are chromosome breakage, sister chromatid exchange (SCE), thymine base damage, and cell nuclei aberrations. There is no reliable evidence for classical chromosome breakage using ultrasound[1]. Miller has extensively reviewed the SCE work and concluded that most of the evidence suggests that ultrasound does not induce SCE[58]. Thymine base damage and cell nuclei aberrations have been

observed in vitro at intensities used in physical therapy[59,60]. It is important to realize that DNA damage is only of hereditary significance if the damaged DNA is incorporated into surviving cells. The two in vitro studies mentioned above indicated that cell death was the most likely outcome[59,60]. However, a recent unconfirmed study[61] suggests that ultrasound may be a weak mutagen if the acoustic pressure is high enough to produce transient cavitation. The possibility of genetic damage due to this mechanism needs to be explored further.

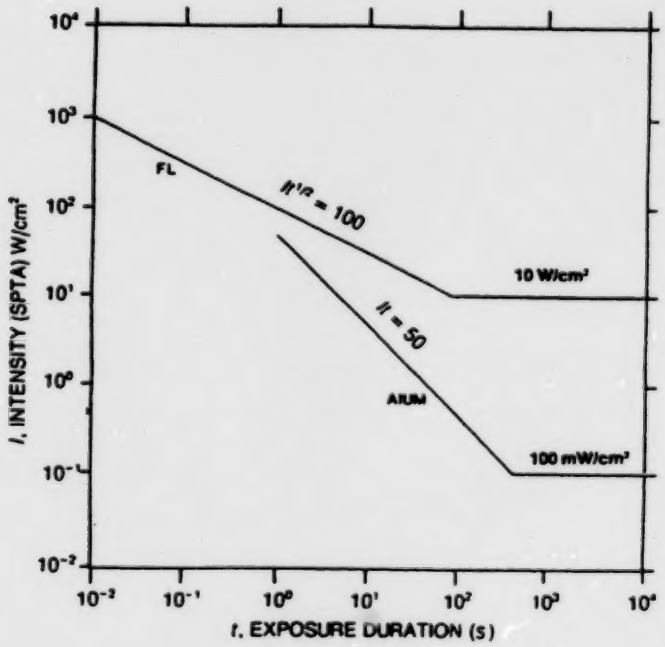
2.3 Mammalian In Vivo Studies

The most extensively studied endpoints in mammalian systems include weight reduction, mortality and morphological abnormalities. These effects have been recently reviewed[32].

One can summarize the results graphically with plots of acoustical exposure conditions (intensity versus dwell time). The areas below the curves indicate exposure values for which no biological effects have been observed in mammalian in vivo studies. Such curves provide a guide to those exposure conditions which, based on current data, could be of concern. However, it is important to realize that such curves do not represent universal exposure criteria. In Figure 2.1 two curves are shown. The curve marked FL refers to focal lesions (tissue damage in a localized region). The plot marked AIUM refers to any significant biological effect. It is a graphical representation of a statement (see page 25) adopted by the AIUM Bioeffects Committee[19]. The rationale behind this statement has been given by Nyborg[25].

Except for the violations possible with the pulses from extracorporeal shock wave lithotripters, this statement still appeared to be valid as of January 1988. It should be noted that at present there are some mammalian in vivo studies which have reported effects at I(SPTA) values as low as 10 mW/cm^2[28], but there has yet to be independent confirmation of these studies. A number of other studies over the past decade indicated that biological effects on mammalian tissue in vivo could occur at I(SPTA) values in the range 10-100 mW/cm^2. However, they have either been directly refuted or, at least, have not been reproduced in other laboratories[28].

Figure 2.1 Plots of Biological Effects Curves Showing Lowest Intensities at Which Confirmed Significant Effects Have Been Observed in In Vivo Mammalian Tissues



The upper plot (FL) applies to focal lesions; the intensities are those found at the site of the lesion (in situ). The lower curve (AIUM) is a graphical representation of the AIUM Statement[19] and the intensities are free-field exposure parameters as measured in water. Figure from NCRP Report No. 74[1].

"STATEMENT OF MAMMALIAN IN VIVO ULTRASONIC BIOLOGICAL EFFECTS August 1976; Revised October 1978; Reaffirmed October 1982.

In the low megahertz frequency range there have been (as of this date) no independently confirmed significant biological effects in mammalian tissue exposed to intensities* below 100 mW/cm^2. Furthermore, for ultrasonic exposure times** less than 500 seconds and greater than one second, such effects have not been demonstrated even at higher intensities, when the product of intensity* and exposure time** is less than 50 joules/cm^2.

*Spatial peak, temporal average as measured in a free field in water.

**Total time; this includes off-time as well as on-time for a repeated pulse regime."

3. HUMAN EXPOSURE TO ULTRASOUND

3.1 Physical Therapy

Ultrasound physical therapy has been a widely used technique in Canada for at least a decade. Estimates[42] indicated that, in 1977, about 4% of the Canadian population had ultrasound physiotherapy treatment. There is a wide variety of ultrasound applications in physical therapy such as:

(i) Treatment of soft-tissue lesions

In conditions such as tennis elbow, bursitis, and low back pain, ultrasound is given to decrease pain, muscle spasm, stiffness, and to increase the resolution of inflammatory swelling[26]. Ultrasound in physiotherapy is probably most commonly used for the treatment of these conditions. Recent clinical trials support some of these treatments[62,63].

(ii) Stimulation of tissue repair

In the repair stages of soft tissue lesions, ultrasound is used to increase the rate of healing. Dyson and others studied this effect on a variety of skin lesions and more recently, on bone repair[64]. The primary mechanism of action of ultrasound is not established but it appears to be non-thermal.

(iii) Treatment of collagenous contractures, adhesions, and scars

Ultrasound, by its thermal effect, can increase the extensibility of collagen-rich tissue such as tendons, ligaments, and joint capsules. This is probably the best established but least used application of ultrasound. Such treatment increases the effectiveness of subsequent physical therapy procedures such as stretching and therapeutic exercise to improve joint range of motion and tissue mobility[26]. The advantages of ultrasound over other thermal agents are: (i) superior depth of penetration, (ii) preferential heating of collagen-rich tissue, particularly at soft-tissue/bone interfaces and (iii) the ability of the operator to control the direction of the beam and to localise the treatment to the target area.

Typical values of time average effective intensity used in therapy are in the range of 0.5-2.5 W/cm^2 in continuous mode. When non-thermal effects are required, the pulsed mode is used with temporal maximum effective ultrasonic intensities of 0.5-1.0 W/cm^2 and ratios of temporal maximum to temporal average effective intensity ranging from 2 to 10.

Detailed reviews of the uses of ultrasound in physical therapy can be found elsewhere[26,64].

3.2 Diagnostic Ultrasound

In the last decade, exposure to diagnostic ultrasound has increased dramatically. At present, it is estimated that up to 80% of all newborns are exposed to ultrasound at least once prior to birth[65]. There are many different diagnostic ultrasound applications. The most important and widespread

are those in obstetrics and cardiology. Other frequent uses include gynecological and abdominal examinations. In addition, there are urological, vascular, breast, eye and thyroid ultrasound examinations. Most clinical imaging is performed with real-time scanning equipment. These units provide cross-sectional images of moving structures in the body. Ultrasound transmitted into the body is received as echoes from the body tissues and fluids. Different tissues send back different echo amplitudes and most interfaces between body structures can be discerned. Hence an image of the internal anatomy of the body can be obtained. Motion or fluid flow in the body can also be monitored using the Doppler ultrasound technique. Ultrasound shifts frequency when scattered or reflected from a moving target and these frequency shifts can be accurately measured. In this way, the beating heart can be monitored or blood flow can be measured. In another technique (M-mode imaging) heart function can also be observed and measured by displaying the motion of cardiac structures over time.

The benefits of diagnostic ultrasound are well established when clinical indications are present. However, routine use of real-time scanning, as some advocate for obstetrics, is still controversial[30,66].

There is a wide range of output intensities characteristic of different types of diagnostic units. Surprisingly, even devices with the same claimed purpose can have a wide range of intensities depending on the manufacturer[1,15,67,68]. This is shown in Figures 3.1, 3.2 and 3.3. The wide range of diagnostic ultrasound output levels suggests that there may be unnecessary exposure to ultrasound during clinical examinations.

Furthermore, with the recent development of fetal blood flow examinations, ultrasound exposures of the fetus are being done with high output Doppler ultrasound devices. These devices were not necessarily sold for the intended use of fetal examinations. Their I(SPTA) values range from about 150 mW/cm^2 to 3000 mW/cm^2 as indicated in a survey of manufacturers conducted in 1984/85 by the Bureau of Radiation and Medical Devices. These exposures are much greater than those to which the fetus is typically exposed in real-time B-mode imaging.

Figure 3.1 Plots of Ultrasound Exposure Parameter Values for Diagnostic Pulsed Ultrasound

The range of intensities for pulse echo ultrasound are plotted as a function of relevant measures of the time. The intensity I_m is the largest half-cycle intensity during a pulse. The I(SPTA) values are compared to the biological effects curves of Figure 2.4 and values commonly used for continuous wave therapy applications. From NCRP Report No. 74[1].

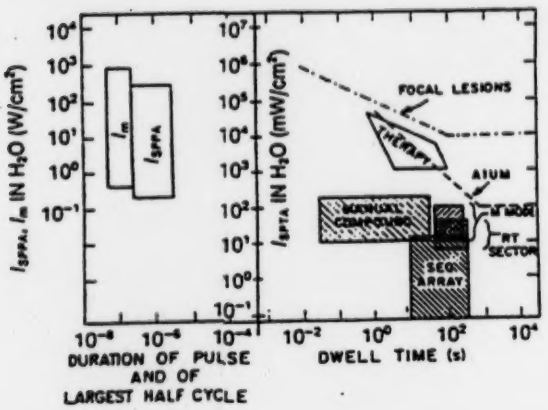
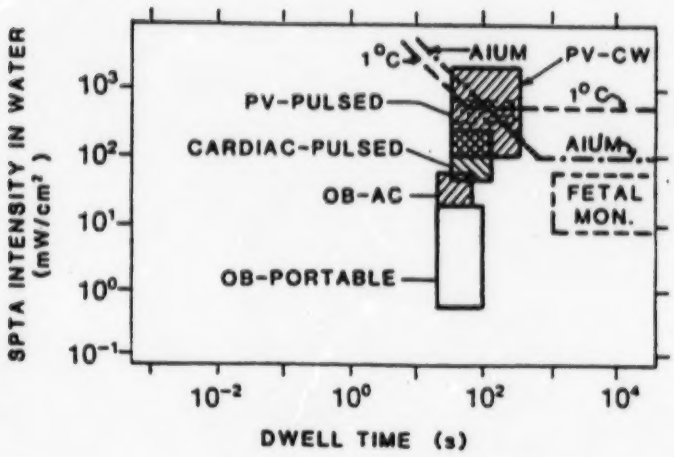


Figure 3.2 Plots of Exposure Parameter Values (I(SPTA)) for Doppler Diagnostic Devices



I(SPTA) is plotted as a function of dwell time. Doppler instrument classes are: PV-CW, peripheral vascular, continuous wave; PV-PULSED, peripheral vascular, pulsed; AC powered (OB-AC) and portable (OB-PORTABLE) obstetrical (fetal life detecting) and fetal monitoring. The curve labeled 1°C is a calculated result specifying the intensity/time condition leading to a temperature rise of 1°C at 2 cm from a transducer with a beam diameter of 0.4 cm. The frequency is 10 MHz and the coefficients of attenuation and absorption are both equal to 4.3 dB/cm. Blood flow cooling is not included in the model. Details of the model used to calculate this curve are given in NCRP Report No. 74[1]. Figure is from this reference.

Figure 3.3 Histograms of Number of Devices Sold in Canada as a Function of I(SPPA)

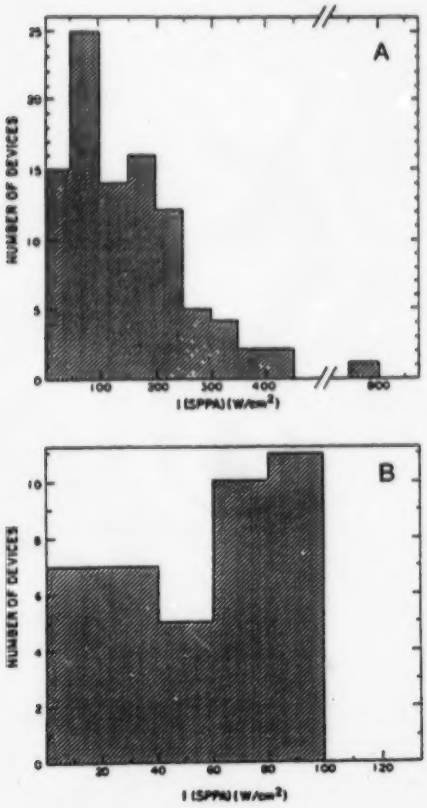


Figure 3.3B is an enlargement of the lowest two intervals of Figure 3.3A. All devices had the claimed purpose of obstetrical use. Values of I(SPPA) were reported by the manufacturers.

3.3 Surgical Applications and Hyperthermia

The use of ultrasound in surgery and hyperthermia has been a relatively recent development in Canada and, to date, these modalities have gained only limited use. A 1977 survey[42] indicated that there was no reported usage of ultrasound for surgery or hyperthermia in Canada.

By using high intensity ultrasound, pathological tissue can, in favourable cases, be destroyed selectively by heating. This gives rise to the surgical use of ultrasound for the treatment of Menière's Disease and glaucoma at MHz frequencies. At kHz frequencies (20-40 kHz) phacofragmentation, the destruction of cataracts, percutaneous lithotripsy, and other surgical procedures can be performed. Another developing method is hyperthermia for the treatment of cancer. This method is based on the selective heating of tumour tissue by ultrasound. Intensities for surgical application are greater than 20 W/cm^2 I(SPTA). For hyperthermia they are about 1 W/cm^2[1].

Possibly, the most rapidly growing exposure to an ultrasonic surgical device is via extracorporeal shock wave lithotripters which utilize an acoustic shock wave to break up kidney stones[69].

4. SAFE USE GUIDELINES

4.1 Ultrasound Physical Therapy

4.1.1 Ultrasound Therapy Devices Regulations

A common conclusion from surveys conducted since 1974[70-74] on the clinical use of ultrasound therapy devices was that these devices were generally unable to deliver prescribed doses to patients with a reasonable degree of accuracy. This occurred because the indicated output of the device often had little relation to the actual acoustic output. Excessive exposures either lead to unnecessary risk or fail to achieve clinical benefit. Inadequate exposures fail to achieve clinical benefit resulting in an unnecessary exposure to ultrasound. Since the intensity levels used in ultrasound therapy are in the range where adverse biological effects have been observed in animal studies, it is essential that the treatment doses are indicated and delivered accurately.

To ensure that new devices can deliver prescribed exposures, the Canadian Ultrasound Therapy Devices Regulation[75] was promulgated under the Radiation Emitting Devices Act[76] in 1981 and amended in 1984.

The requirements include a number of specifications for the safe use of ultrasound therapy devices. They may be divided into the following four areas: (1) indicators; (2) labelling; (3) output control; and (4) timer specifications.

An important feature of the regulation is that the maximum temporal average effective ultrasonic intensity must not exceed 3 W/cm^2. This value was chosen for several reasons: (i) higher intensities do not seem to be required for efficacy. Survey data indicate that 3 W/cm^2 is commonly found as the maximum nominal intensity available for most devices. This intensity value has been accepted by European manufacturers for many years as the maximum necessary for therapy. (ii) Higher intensities may be painful or damaging. For example, the work of Payton et al.[43] suggests that intensities above 3 W/cm^2 applied near a bone would either be unbearable or cause bone damage. Other studies noted by Lehmann[26] suggested that damage tended to occur for intensities greater than 3 W/cm^2. Spatially non-uniform beams with temporal average effective ultrasonic intensities greater than 3 W/cm^2 could have I(SPTA) in situ intensities substantially higher than the focal lesion curve of Figure 2.1.

The entire regulation is given in Appendix I.

4.1.2 Care of Equipment

Calibration - It is recommended that ultrasound therapy devices be calibrated by suitably trained personnel at least once each month[74] to ensure that the ultrasonic power is indicated with an accuracy of ±20%. The timer accuracy should also be checked to ensure that it has the accuracy stated in Appendix 1. These procedures should also be performed upon delivery of the device. A list of power meters and hydrophones is available from the Bureau of Radiation and Medical Devices on request.

Maintenance - Mechanical shocks and overheating of either the applicator or housing must be avoided. Abrasives or chemicals must not be used on the applicator face. If such action occurs, or is suspected, the ultrasonic power calibration should be checked.

Testing of Applicator - To avoid applicator equipment damage, it should not be tested by placing droplets of water on its face and by seeing if they vaporize in order to ascertain the emission of ultrasound. A better practice is to immerse the applicator head in a basin of water, point the beam towards the side of the container, and observe whether the sound waves cause ripples at the edge of the basin.

4.1.3 Operator Safety Precautions

Operators of ultrasound therapy devices should minimize exposure to themselves as follows:

(a) The applicator face must not be touched by the operator when the device is emitting ultrasound.

(b) The operator must not immerse any part of his/her body in the water bath in the path of the direct transmitted beam, while an ultrasound therapy device is operating in that water bath.

(c) Ultrasound therapy devices should only be turned on when the face of the applicator is in acceptable acoustic contact with the patient, and the operator is holding the applicator by its handle. Adherence to this guideline also reduces the possibility of thermal damage to the applicator.

(d) To help avoid any reflected or scattered ultrasound from entering the operator's hand during underwater treatments, a dry soft knit glove may be worn inside a rubber glove to provide air-gap protection.

4.1.4 Patient Safety Precautions

To minimize potential adverse health effects, the operator should use the minimum patient exposure required to achieve the desired benefit.

The operator should be present all the time during an ultrasound exposure, so the intensity can be reduced or the treatment can be terminated if the patient shows the least sign of distress.

Records should be kept of each patient, noting the exposure levels, times, and couplant used. Maintaining well documented, reproducible exposure conditions, should help minimize unnecessary exposure.

Since ultrasound is almost totally reflected at an air-tissue interface, coupling media must always be used between the applicator surface and the patient. Poor coupling could lead to all or most of the ultrasound energy being dissipated in the applicator. Subsequent heating of the applicator could either damage it and/or burn the patient. Furthermore, where a significant fraction of the ultrasound beam is expected to propagate to the site of exit from the body, it may be advisable to avoid undesirable reflections by ensuring that the region being treated is coupled to, and rests on, an absorber.

The transducer should be kept moving slowly, angled at 90° to the treatment area, during the course of treatment to minimize the risk of causing hot spots (undue temperature rise in a single volume of tissue receiving excess exposure). Another reason to avoid the use of a stationary transducer concerns the danger that the peak intensity will remain over the same tissue for the full treatment and prolonged standing waves could develop. Prolonged standing waves might result in blood flow arrest and cause possible damage to the endothelial cells in the blood vessel walls. This could also lead to the formation of blood clots[47].

If any pain or uncomfortable "prickly" sensation is felt by the patient, this may be an indication that the bones or nerve endings in the vicinity of the ultrasonic beam are becoming, or are already, overheated. In this case the ultrasound power or intensity must be immediately reduced.

4.1.5 Contraindications

Contraindications to ultrasound therapy have been listed in several publications[1,26,64]. Some of these are based on a general understanding of the principles and practice of ultrasound therapy. Others may arise from extrapolation of

specific scientific experiments or are based on the personal clinical experience of the physiotherapists listing the contraindications. The following list is similar to that of Reid[77] and Oakley[78]. Where possible, other references or rationales for the contraindications are also given.

Ultrasound physical therapy should not be applied to any patient with obtunded reflexes or to any area with significantly diminished pain sensitivity or heat sensitivity[1,26,77,78].

No pregnant or potentially pregnant patient should ever receive ultrasound therapy in any area of the body which is likely to result in exposure to the fetus. Overheating of the fetus could result. The fetus is at particularly high risk during the first trimester, during the period of organogenesis[1,57,77,78].

Ultrasound should not be applied to the eye in physiotherapy procedures since the lens has limited means (due to being avascular), for removing heat and has a relatively high absorption coefficient. Similarly, any region of significantly diminished blood circulation should not undergo irradiation, except at low intensities where wound healing may be expected[1,26,77,78].

Ultrasound should not be applied to the brain, spinal cord or large subcutaneous peripheral nerves[77,78].

To avoid the possibility of spinal cord damage, it is advisable to avoid using ultrasound over the vertebral column following laminectomies or when any anaesthetic area is involved[26,77].

Ultrasound physical therapy should not be applied to the reproductive organs[26,77,78].

Care should be taken not to irradiate neoplastic tissues as there is some evidence that inappropriate heating patterns, giving rise to temperatures less than 42°C, may stimulate tumor growth or promote metastases[1,77-79].

Care should be taken not to irradiate epiphyseal lines in children[26].

Treatment of acute infection of bone or tissue should not be carried out as the treatment could force areas of pus into surrounding tissue, thereby spreading infection[26,77,78].

Ultrasound should not be used in the thoracic area if the patient has a cardiac pacemaker of any kind[1,78].

Blood vessels in poor condition should not be treated as the vessel walls may rupture as a result of the exposure[78].

Patients suffering from cardiac disease should not receive treatment over the cervical ganglia, the stellate ganglion, the thorax in the region of the heart, or the vagus nerve, as a reflex coronary vasospasm might result. Only low intensities and short treatment times should be used if these patients are treated in other areas since the stimulation of practically any afferent autonomic nerve (especially the vagus nerve) in the body may cause a change in cardiac rate[77,78].

Patients with thrombophlebitis or other potentially thromboembolic diseases should not be treated since a partially disintegrated clot could result in an obstruction of the arterial supply to the brain, heart or lungs[77,78].

4.1.6 Operator Training

Skilled personnel using reliable and accurately calibrated equipment are necessary to deliver prescribed doses of ultrasound to patients both safely and effectively. Improper training increases the risk of incorrect usage which can, at best, reduce the benefits of ultrasound and, at worst, result in tissue damage.

Therefore operators should have successfully completed a recognized course in ultrasound therapy which should include instruction in: basic physics, instrumentation, biological effects of ultrasound, indications and contraindications, dosage prescription, and application techniques. A sound knowledge of anatomy, particularly surface anatomy, is an essential prerequisite.

Courses are available in eleven universities across Canada in their programs of Physical Therapy or Rehabilitation. A list of these courses is available from the Canadian Physiotherapy Association in Toronto.

4.2 Diagnostic Ultrasound

4.2.1 Diagnostic Ultrasound Devices Regulations

There are currently no regulations in Canada for diagnostic ultrasound devices. However, in consideration of the following:

(i) large population exposure of future generations

(ii) fetal exposures with new devices having relatively high acoustic output

(iii) continued uncertainty about biological effects

(iv) apparently unnecessary radiation exposure as suggested by the wide range of intensities for devices with a single claimed purpose

the Bureau of Radiation and Medical Devices is actively developing regulations under the Radiation Emitting Devices Act for diagnostic ultrasound devices. At present, it is recommended that device labelling, complies with the requirements of the AIUM/NEMA labelling standard[16] (currently under revision, with completion expected before 1989). The labelled values of exposure parameters and associated quantities should be those measured in water.

4.2.2 Exposure Levels

Ideal recommendations on exposure criteria for diagnostic ultrasound cannot be made since insufficient data exists to weigh risk against benefit[80]. It is difficult to determine exactly which levels constitute unnecessary, potentially hazardous radiation.

In light of the above, the following guidelines are recommended for device labelling, design and construction.

1. Labelling of diagnostic ultrasound devices should be in compliance with the AIUM/NEMA labelling standard[1,16] as indicated above.

2. Ultrasound equipment should be designed so that the maximum levels of the various intensities which the equipment can produce are as low as practicable for the anticipated uses of the equipment[1,16].

3. Where such flexibility is consistent with reasonable cost and performance of the system, operators should be able to adjust controls to use the minimum acoustical exposure[1,16].

4. Where the ultrasonic power is adjustable, it is recommended that the "hard copy" from a diagnostic procedure state the percentage of maximum power used. This will ensure reproducibility of exposure conditions.

5. In order that measurements of ultrasonic exposure levels can be made by the user or a measurement service contracted by the user, as part of a quality assurance program, it is recommended[20] that an electrical signal to trigger the measurement system, should be provided synchronized to the excitation of the ultrasonic transducer or each ultrasonic transducer element group. For automatic scanning systems an additional trigger signal should be provided synchronized to each acoustic repetition period. This should permit observation of the received signal at a hydrophone from any chosen ultrasonic scan line.

Specific guidelines for cautionary labelling and criteria for user controls for diagnostic ultrasound devices with the claimed purpose of fetal examinations are given in Appendix 2.

4.2.3 Care of Equipment

Quality assurance tests, using commercially available phantoms or test objects, should be performed as often as feasible, subject to the apparent stability of the device. Acceptance testing should also be performed upon delivery of

the device. A reasonable minimum frequency for quality assurance testing is suggested in a draft report of NCRP Committee No. 70[81]. Simple tests of sensitivity and measurement accuracy should be carried out monthly. More complex tests such as grey scale dynamic range and spatial resolution should be made annually. A more complete schedule is given in the NCRP report. More frequent testing may be needed subject to the apparent stability of the device. This is particularly true for older equipment or, for example, if a transducer has been improperly handled.

Several other quality assurance guidelines exist[82-84] and both the American Institute for Ultrasound in Medicine/National Electrical Manufacturers' Association as well as the International Electrotechnical Commission are working on new standards. These new standards should resolve some of the difficulties recently found, such as evaluation of lateral resolution with some real time scanners[85] and the lack of a method to test for resolution in the elevation plane of linear arrays.

A list of commercially available phantoms and test objects may be obtained, on request, from the Bureau of Radiation and Medical Devices.

4.2.4 Use of Equipment

The use of diagnostic ultrasound radiation to obtain information about function or structure in human beings should be limited to the following situations:

(i) in the ill, potentially ill or pregnant patient, when the medical benefit which may accrue from the diagnostic data clearly outweighs any foreseeable risk; and

(ii) in situations of training, demonstration or research where there is expectation of medical benefit, the risk is considered to be very small and is ethically accepted, provided that it has been explained to, and accepted by, the patient or volunteer.

These guidelines would indicate that ultrasound should not be used solely to have a picture of the fetus, solely to learn the sex of the fetus, or solely for commercial purposes[30]. In situations of training, demonstration or research, benefits in the form of increased medical knowledge and/or improved patient care must be expected from the person's exposure[86]. Furthermore, in these situations, the subject should be informed of the anticipated exposure conditions and how these compare with conditions for normal diagnostic practice[87].

Further guidelines are as follows:

(iii) In clinical practice, users should know the values of the exposure parameters of the ultrasound equipment they employ. They should be thoroughly acquainted with the meaning and significance of these parameters[1,16,19].

(iv) Users should strive to obtain the most medically significant information possible while producing the least ultrasonic exposure to the patient[1].

With this latter recommendation in mind, the values of the exposure parameters from diagnostic equipment should become a factor in the purchase of any diagnostic ultrasound equipment[19]. In addition, output controls should be utilized to minimize ultrasonic exposure. Furthermore, particularly for obstetrical examinations, it would be desirable if the transducer was not coupled to the patient during operation in freeze-frame mode, since ultrasonic transmission may still be occurring.

4.2.5 Operator Training

Highly skilled personnel are necessary to produce useful ultrasound images and/or Doppler information. Without adequate training, more and longer ultrasonic scans are necessary to obtain a minimum amount of diagnostic information. This means a greater exposure of ultrasound radiation to the patient and in many cases, inferior diagnostic information.

At present, it is recommended that diagnostic medical sonographers have successfully completed a recognized one-year training program. A list of such programs in Canada is available from the Canadian Society of Diagnostic Medical Sonographers. This basic training should include instructions in: operator techniques and interpretation of diagnostic ultrasound information, performance measurements and procedures, biological effects of ultrasound radiation, basic physics, instrumentation, and quality assurance. This training should be completed with the passing of a certification examination consistent with the examinations of the American Registry of Diagnostic Medical Sonographers.

For physicians who have completed a residency without formal training in ultrasound, it is recommended that they complete successfully a minimum of three months training. This should include one month of supervised basic training, as outlined above, and two months of supervised practical training including more than 200 examinations. After this training it is expected that the user will maintain continued education in what is still a rapidly developing field[88].

It is recommended that every obstetrician and gynecologist undergo a three-month training program in ultrasound during his/her residency training program[89].

Furthermore, it is recommended that graduating radiology residents should have completed a minimum of six months training in ultrasound.

4.3 Surgical Ultrasound and Hyperthermia

Surgical uses of ultrasound fall into three main categories: (i) very intense focused ultrasound used to produce a focal lesion in pathological tissue (at MHz frequencies), (ii) the mechanical effects of ultrasound used to cut and emulsify pathological tissue (at kHz frequencies), (iii) focused shock waves used to fragment kidney stones (extra corporeal shock wave lithotripsy (ESWL)). In hyperthermia, the objective is to kill cancerous tissue by reaching destructive temperatures while sparing normal tissue.

By virtue of their destructive nature, exposure limits are not practical for these modalities. However, carefully defined dosimetry is required for focal lesion surgery and hyperthermia. Well defined vibration amplitudes are required for the mechanical surgical techniques.

At present the use of ultrasound in surgery and hyperthermia appears to be limited. In a 1977 survey[42] no surgical applications were found. Although, at present, surgical applications are known, the growth of these techniques, with the possible exception of ESWL is, as yet, not rapid. Furthermore, there have been no reports of improper use or poor commercial equipment design. Since the various techniques depend very specifically on the interaction of ultrasound with tissue, specific detailed guidelines for each use would have to be devised if warranted. At present, the limited use and apparently skillful application and design of ultrasound surgical devices do not warrant detailed guidelines. Hence, only a few general guidelines are given. These are:

1. Treatments should be performed on patients only where there are clinical indications that this is necessary;

2. The lowest ultrasound output to perform the desired purpose successfully should be used;

3. Treatments should only be performed at the hands of skilled operators;

4. Maintenance and calibration of devices is essential;

5. Ultrasound irradiation of the pregnant or potentially pregnant uterus should be avoided during any ultrasound surgical or hyperthermia procedure.

APPENDIX 1

Radiation Emitting Devices Regulations for Ultrasound Therapy Devices

SCHEDULE I

13. Ultrasound therapy devices, being devices designed to generate and emit ultrasonic power at acoustic frequencies above 20 kHz for use in physical therapy

SCHEDULE II

PART XIII*
Ultrasound Therapy Devices

Interpretation

1. In this Part and in item 13 of Schedule I,

"amplitude modulated wave" means a wave in which the ratio of the temporal maximum pressure amplitude to the root-mean square pressure amplitude, each spatially averaged over the effective radiating surface is greater than 1.05; (*onde modulée en amplitude*)

"applicator" means the part of the ultrasound therapy device designed to transmit ultrasonic power from the transducer to a patient and includes the transducer and any associated housing; (*applicateur*)

"continuous wave"means a wave in which the ratio of the temporal maximum pressure amplitude to the root-mean square pressure amplitude, each spatially averaged over the effective radiating surface, is less than or equal to 1.05; (*onde entretenue*)

"control panel" means that portion of the external surface of the housing on which the user controls are mounted; (*tableau de commande*)

"effective radiating area" means the area of the effective radiating surface that encompasses all points at which the ultrasonic intensity is equal to or greater than 5% of the maximum spatial ultrasonic intensity at the effective radiating surface, expressed in square centimeters (cm^2); (*aire émettrice utile*)**

"effective radiating surface" means the surface covering all points that are 5 mm from the applicator face; (*surface émettrice utile*)

"effective ultrasonic intensity", with respect to ultrasonic power, means**

(a) in the case of a focussing applicator, the quotient obtained by dividing the amount of the ultrasonic power by the amount of the focal area, and

(b) in any other case, the quotient obtained by dividing the amount of the ultrasonic power by the amount of the effective radiating area; (*intensité ultrasonore utile*)

"focal area" means the area of the focal surface expressed in square centimeters (cm^2); (*aire focale*)

"focal length" in respect of a focussing applicator, means the distance in centimeters between

(a) that point of the effective radiating surface the coordinates of which are the mean values of the coordinates of the points of that surface, and

(b) that point of the focal surface the coordinates of which are the mean values of the coordinates of the points of that surface; (*longueur focale*)

"focal surface" in respect of a focussing applicator, means the beam cross-section with the smallest area; (*surface focale*)

"focussing applicator" means an applicator in which the quotient of the area of the surface having the smallest area, in any plane consisting of the points

at which the ultrasonic intensity is greater than 5% of the maximum intensity in that plane, and the effective radiating area is less than one-half; (*applicateur focalisant*)

"housing" means a structure that encloses

(a) that portion of a fully assembled ultrasound therapy device that supplies the electrical energy to the applicator, and

(b) the electrical circuitry of the device; (*logement*)

"pressure amplitude" means the instantaneous value of the modulating waveform in the following equation:**

p(t)=p1(t)p2(t)

where p(t) is the instantaneous pressure,

p1(t) is the modulating wave form,

p2(t) is the relative amplitude of the carrier wave normalized to a peak height of one,

p(t), p1(t) and p2(t) are periodic functions of time, t, at any point in space, and

the period of p1(t) is greater than the period p2(t); (*amplitude de pression*)

"pulse duration" means a time interval, expressed in seconds, beginning at the first time the pressure amplitude exceeds the value that equals the sum of the minimum pressure amplitude and 10% of the difference between the maximum and minimum pressure amplitudes and ending at the last time the pressure amplitude returns to that value; (*durée des impulsions*)**

"pulse repetition rate" means the repetition frequency of the wave shape that modulates the ultrasonic radiation carrier wave expressed in pulses per second (pps); *(taux de répétition des impulsions)*

"service controls" means controls provided by the manufacturer for adjusting the ultrasound therapy device that, under normal conditions of use, are not accessible to the user; (*commandes internes*)

"ultrasonic frequency" means the frequency of the ultrasonic power wave, expressed in kilohertz (kHz) or megahertz (MHz); (*fréquence*)

"ultrasonic power" means the total power that is emitted in the form of ultrasonic radiation by the applicator and that is averaged over each cycle of the ultrasonic radiation carrier wave, expressed in watts (W); (*puissance acoustique*)

"user controls" means controls provided by the manufacturer for operating the ultrasound therapy device that, under normal conditions of use, are accessible to the user. (*commandes externes*)

Standards of Design and Construction

2.(1)Every ultrasound therapy device shall be designed and constructed in such a manner that, under the conditions of use specified by the manufacturer, it functions in accordance with section 3 for as long as the device has its original components or replacement components recommended by the manufacturer.

(2) Every ultrasound therapy device shall be designed in such a manner that

(a) all marks, labels and signs are permanently affixed thereon and clearly visible; and

(b) all user controls, meters, lights or other indicators are clearly visible, readily discernible and clearly labelled to indicate their function.

(3) Every ultrasound therapy device shall bear

(a) on the external surface of its housing

(i) the name and address of the manufacturer,

(ii) the name and address of the distributor, if the distributor is not the manufacturer,

(iii) the type and model designation,

(iv) the serial number,

(v) the month and year of manufacture,

(vi) the ultrasonic frequencies in kilohertz (kHz) or megahertz (MHz),

(vii) a statement indicating whether the wave produced by the device is a continuous wave or an amplitude modulated wave,**

(viii) in the case of a device that produces an amplitude modulated wave,**

(A)the pulse repetition rate, the pulse duration, the ratio of the temporal maximum effective ultrasonic intensity to the temporal average effective ultrasonic intensity, and a description of the wave shape, where these parameters do not vary depending on the power, and

(B)the pulse repetition rate, the pulse duration, the ratio of the temporal maximum effective ultrasonic intensity to the temporal average effective ultrasonic intensity, and a description of the wave shape, all at temporal maximum ultrasonic power where these parameters do vary depending on the power,

(ix) the line voltage used for normal operation, and**

(x) the ultrasound radiation warning sign described in section 4; and**

(b) on the external surface of each applicator

(i) the identification of the type and model of the ultrasound therapy device for which it is designed,

(ii) where an applicator is a focussing applicator, the focal length and the focal area,

(iii) a unique serial number or other unique identification, and**

(iv) the effective radiating area in square centimeters (cm^2).

(4) Every ultrasound therapy device shall be designed and constructed to include the following safety features:

(a) on the control panel, separate indicator lights or other equivalent indicators that have an expected lifetime of at least 5000 hours,

(i) to show when the line voltage is "ON" or "OFF", and

(ii) to show when the ultrasonic power is being applied to the applicator;**

(b) a power indicator that

(i) in the case of a device that produces a continuous wave, shows by a direct reading the level of the temporal average ultrasonic power and the temporal average effective ultrasonic intensity,*

(ii) in the case of a device that produces an amplitude modulated wave, shows by a direct reading the level of the temporal maximum ultrasonic power and the temporal maximum effective ultrasonic intensity, and**

(iii) functions in accordance with section 3;

(c) a clear and reliable indicator of the range used, if the power indicator described in paragraph (b) utilizes two or more different ranges of measurement; and

(d) a timer that

(i) terminates the generation of ultrasound after a preset time interval and then returns to zero,

(ii) does not allow the generation of ultrasound with the timer set at zero,

(iii) is adjustable to settings in increments not greater than one minute, and

(iv) functions in accordance with section 3.

(5) Where an ultrasound therapy device is equipped with an ultrasonic power control, that control shall

(a) allow the adjustment of ultrasonic power;

(b) have a minimum and maximum adjustment that directly relates to the ultrasonic power level indicator; and

(c) function in accordance with section 3.

Standards of Functioning

3.(1)Every ultrasound therapy device shall function in such a manner that when the device is operating with its user controls adjusted to yield the maximum temporal average-spatial average effective ultrasonic intensity, such intensity shall not exceed 3 W/cm^2, when measured in accordance with subsection (2).**

(2) The method used to measure the effective ultrasonic intensity for the purposes of subsection (1) shall produce a result that is at least as accurate as the result that would be produced by using**

a) an ultrasound balance radiometer to measure the ultrasonic power; and

(b) an ultrasound detector of dimensions less than one wavelength in water to measure the pulse repetition rate, the pulse duration and the effective radiating area.

(3) The power indicator referred to in paragraph 2(4)*(b)* shall show on the scale of the ultrasonic power control or on the output power meter the ultrasonic power with an accuracy of ±20% when the output is greater than 10% of the maximum ultrasonic power.

(4) The timer referred to in paragraph 2(4)*(d)* shall be accurate to within 30 seconds for settings less than 5 minutes, to within 10% for settings from 5 to 10 minutes, and to within 1 minute for setting greater than 10 minutes.**
(5) The ultrasonic power output shall remain constant within ±20% of its initial value during one hour of continuous operation, at maximum output and at rated supply line voltage, in water at a temperature of 22°C±3°C.
(6) The actual ultrasonic frequency of an ultrasound therapy device shall not differ more than ±5% from the ultrasonic frequency of the device that is stated on the external surface of the housing of the device pursuant to subparagraph 2(3)*(a)*(vi).**
(7) The effective radiating area shall be kept within ±20% of the rated value given by the manufacturer.

Warning Sign Specifications

4. The warning sign referred to in subparagraph 2(3)*(a)*(x) is a sign that**
   (a) is shown in two contrasting colours;
   (b) is clearly visible and identifiable from a distance of 1 m;
   (c) has no outer dimensions less than 2 cm;
   (d) bears the words "CAUTION-ULTRASOUND, ATTENTION-ULTRASONS"; and
   (e) is designed in accordance with the following diagram:

* *P.C. 1981-908, April 2, 1981*
** *P.C. 1984-3737, November 22, 1984*

APPENDIX 2

Proposed Quantitative Guidelines for Diagnostic Ultrasound Devices with the Claimed Purpose of Fetal Examinations*

Guideline 1

If the maximum I(SPTA) value+ of all modes claimed for fetal use exceeds 100 mW/cm^2, then the device should be equipped with an acoustic exposure control enabling the reduction of I(SPTA) in these modes. This reduction should occur via adjustment of the temporal peak voltage applied to the transducer in increments which are as small as feasible, and in any case, no greater than 3 dB. The minimum usable I(SPTA) value should be as low as feasible, and, in any case, less than 100 mW/cm^2.

In addition, where such a user output control is available, the following statement should be included as part of the directions for use: "It is recommended that the output control on the console be used to obtain the minimum I(SPTA) consistent with the most useful diagnostic information".

Rationale

This guideline is proposed to give specific guidance to manufacturers who have devices that produce I(SPTA) values which are always greater than 100 mW/cm^2. Human exposure data (see text) indicates that all fetal heart monitors and most real time imaging modes yield maximum I(SPTA) values much

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*Due to the lack of knowledge of cavitation thresholds and effects in mammals, with microsecond pulses of ultrasound, specific guidelines for I(SPPA) are not prescribed at this time.

+In this Appendix, I(SPTA) is the spatial peak, time-averaged intensity as measured in room temperature water under free-field conditions.

lower than 100 mW/cm^2. Manufacturers of these devices are encouraged to maintain these low values. Furthermore, if a device presently provides output controls down to I(SPTA) values much less than 100 mW/cm^2, manufacturers of these devices are encouraged to maintain these low minimum usable output levels.

The I(SPTA) value of 100 mW/cm^2 was chosen for three reasons: (i) it is the lowest level at which in vivo mammalian biological effects have been confirmed even for unfocused beams and unlimited time duration of exposure, (ii) heating calculations given in NCRP Report No. 74[1] indicate that, for unfocused beams with beamwidths less than 0.8 cm, frequencies between 1 and 7 MHz, and a step-function spatial distribution, maximum temperature rises in soft tissue will not be significantly greater than 1°C with an I(SPTA) value of 100 mW/cm^2, and (iii) it is about a factor of 10 lower than the lowest intensity known to have caused bone damage in animals[77]. Therefore, it is desirable that every user should have the opportunity of setting an I(SPTA) exposure which is at least this low.

Guideline 2

If a device, operating in any mode, yields free-field I(SPTA) values greater than 500 mW/cm^2, then fetal examinations should not be one of the claimed purposes of that mode unless reasonable estimates of the maximum local temperature elevations in fetal tissues, arising from ultrasonic exposures made with the device, are provided in the directions for use.

Rationale

One of the potential hazards of the application of diagnostic ultrasound is that significant heating of the fetus will occur. Since 1°C is the normal diurnal variation in resting temperature, temperature elevations of fetal tissues less than 1°C above normal physiological levels are not of concern[1,90]. However, a temperature rise in fetal tissues to or above 41°C is considered hazardous in fetal exposures[1,57,90]. In order to avoid potentially harmful

ultrasound exposures, the user should be made aware of the maximum expected steady state local temperature elevations in fetal tissues. Of course, no such information need be given in the directions for use when the expected temperature rise would likely be less than 1°C.

It is difficult to predict the conditions under which a 1°C temperature rise might be expected due to the complex relationship between temperature elevation, ultrasonic frequency, beamwidth and I(SPTA). The simple criteria of I(SPTA) of 500 mW/cm^2 stems from an assessment of the results of calculations in NCRP Report No. 74[1] and one of the conclusions from the AIUM Bioeffects Conference[90]. A reasonable extrapolation of this conclusion[90] is that for examinations of soft tissues of the fetus, the computed temperature rise would not be significantly above 1°C, if the I(SPTA) value is less than 1.2 W/cm^2*. However for the same beam, the local temperature rise in fetal bone may be much higher[90].

Calculations in NCRP Report No. 74[1] suggest that for unfocused beams, the steady state temperature rise in soft tissue would not be above 1°C if the I(SPTA) value is less than 250 mW/cm^2+.

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*This conclusion is based on simplified tissue models and simplified models of stationary beams. It states that, for ultrasonic beams with centre frequencies between 2 and 10 MHz and -6 dB beam widths less than 8 wavelengths, the computed temperature rise would not be significantly above 1°C for time average in situ intensities, spatially averaged over the focal area, of 300 mW/cm^2. For the purposes of this Appendix, this value has been converted, by multiplication by a factor of 4, to a free field I(SPTA) water value for the equivalent diffraction focused beam.

+This applies to ultrasonic beams with centre frequencies less than 7 MHz, beamwidths less than 4 mm in diameter and uniform beam profiles for which the spatial average, temporal average intensity is equal to the spatial peak, time average intensity.

The beam characteristics described in the conclusions of the AIUM Conference are similar to those used in many clinical exposures, whereas the unfocused beams described in NCRP Report No. 74 would lead to higher temperatures than expected under most clinical examinations. However, given the uncertainties in the prediction of temperature elevations, a value of 500 mW/cm^2 was selected.

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